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Testing the CGC in proton-lead collisions at the LHC

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Abstract

I present a brief review of present CGC phenomenological applications and of the physics prospects for the forthcoming proton-lead run at the LHC

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Besides its crucial role as a reference experiment to calibrate initial state effects in heavy ion collisions, the forthcoming p+Pb run at the LHC will provide access to kinematic regions never explored so far in nuclear collisions and thus carries great potential for discovery of new QCD phenomena on its own. In particular, the huge leap forward in collision energy with respect to previous high energy electron-nucleus or proton-nucleus experiments¹ will probe the nuclear wave function at values of Bjorken- x smaller than ever before. It is theoretically well established that at small enough values of Bjorken- x QCD enters a novel regime governed by large gluon densities and non-linear coherence phenomena. The Color Glass Condensate (CGC) effective theory provides a consistent framework to study QCD scattering at small- x or high collision energies (for a review see e.g. [1, 2]). It is based on three main physical ingredients: First, high gluon densities correspond to strong classical fields, which permit ab-initio first principles calculation of “wave functions” at small x through classical techniques. Next, quantum corrections are incorporated via non-linear renormalization group equations such as the B-JIMWLK hierarchy or, in the large- N_c limit, the BK equation [3, 4] that describe the evolution of the hadron wave function towards small x . The non-linear, density-dependent terms in the CGC evolution equations are ultimately related to unitarity of the theory and, in the appropriate frame and gauge, can be interpreted as due to gluon recombination processes that tame or *saturate* the growth of gluon densities for modes with transverse momenta below a dynamically generated scale known as the saturation scale, $Q_s(x)$. Finally, the presence of strong color fields $\mathcal{A} \sim 1/g$ leads to breakdown of standard perturbative techniques to describe particle production processes based on a series expansion in powers of the strong coupling g . Terms of order $g\mathcal{A} \sim \mathcal{O}(1)$ need to be resummed to all orders. The CGC provides the tools to perform such resummation although the precise prescription for the resummation may vary from process to process or colliding system

While the CGC has been successfully applied to the description of different observables in different collision systems (from e+p to AA), the p+Pb run at the LHC will provide an excellent –and probably in the near future unique– possibility to disentangle the presently inconclusive situation on the role of CGC effects and also to distinguish among different approaches to describe high energy scattering in nuclear reactions. On the one hand, the LHC shall bring us closer to the limit of asymptotically high energy in which the CGC formalism is developed, thus reducing theoretical uncertainties on its applicability. Equivalently, the value of the saturation scale is expected to be a factor $\sim 2 \div 4$ times larger than at RHIC, so saturation effects should be visible in a larger range of transverse momenta, deeper

¹The expected center of mass collision energy for the p+Pb run is 5 TeV, to be compared to a maximal energy of 200 GeV for RHIC d+Au collisions.

into the perturbative domain. On the other hand, the much extended reach in the LHC will allow measurements far from the kinematic limit up to very forward rapidities, thus minimizing the role of large- x effects which obscured the interpretation of forward RHIC data.

1. Coherence effects in high-energy nuclear collisions

A main lesson learnt from experimental data collected in (d)Au+Au and Pb+Pb collisions at RHIC and the LHC respectively is that bulk particle production in ion-ion collisions is very different from a simple superposition of nucleon-nucleon collisions. Such is evident in terms of the measured charged particle multiplicities, which exhibit a strong deviation from the scaling with the number of nucleon-nucleon collisions: $\frac{dN^{AA}}{d\eta}(\eta = 0) \ll N_{coll} \frac{dN^{AA}}{d\eta}(\eta = 0)$, and also from the non-trivial transverse momentum dependence of nuclear modification factors measured in d+Au collisions. These observations lead to the conclusion that strong coherence effects among the constituent nucleons, or the relevant degrees of freedom at the sub-nucleon level, must be present during the collisions process.

Indeed, and regardless of the question whether the CGC is the most suited framework for their description there is broad consensus that coherence effects are essential for the interpretation of present data on heavy ion collisions. In fact most –if not all– of the different phenomenological approaches for the description of particle production –both in the soft or hard sector–. On physical grounds, coherence phenomena are related to the presence of high gluon densities in the wave function of the colliding nuclei at small values of Bjorken- x ². While a detailed discussion of the different prescriptions found in the literature to account for coherence effects is beyond the scope of this brief review, one can identify in different models coherence effects at the level of the wave function and also at the level of primary particle production, sketched in Fig. 1 (left)³. To the first category correspond the nuclear shadowing (in a partonic language) or the percolation and string fusion (in non-perturbative approaches). In both cases, when different constituents, whichever the degrees of freedom chosen are, overlap in phase space according to some geometric criterium, recombination of such constituents happen, thus reducing the total number of scattering centers –gluons– entering the collision process. Similar phase-space arguments motivate the implementation of energy-dependent cut-offs to regulate independent particle production from different sources, normally a working hypothesis in most Monte Carlo event generators for heavy ion collisions. In Fig 1 (right) we show the collision energy dependence of the transverse momentum cutoff that separates *hard* from *soft* particle production in several event generators for p+p (PYTHIA) and A+A (HYDJETY and HIJING) collisions. Its strong rise with increasing energy signals the increasing importance of collective effects in particle production processes. Also frequent in the literature are the resummation of multiple scatterings, either in a coherent higher twist formalism or in a incoherent *Glauber like* formalism. Finally, the modification of parton distribution functions to allow for the presence of a –normally energy dependent– intrinsic transverse momentum constitute other common practice in phenomenological works. All these ingredients are akin, at least at a conceptual level, to those dynamically built in the CGC, although they are formulated in very different ways. Thus the debate is now which theoretical framework is most suited for their description: whether the CGC (at its present degree of accuracy!) or alternative approaches, typically rooted in the standard collinear factorization framework.

2. State-of-the-art of the CGC formalism and its phenomenological applications

Briefly, it can be said that the CGC is now entering the next-to-leading (NLO) order era. Actually, the kernel of the BK and JIMWLK evolution equations are now known to NLO accuracy [6] or, also, to running coupling accuracy through the resummation of a partial subset of NLO diagrams [7, 8, 9]. In a similar fashion, the following calculations concerning particle production processes have recently become available at NLO accuracy: photon impact factors in deep inelastic scattering [10], full NLO [11] and *inelastic* [12] contributions to hybrid calculation of single inclusive particle production in dilute-dense scattering, running coupling corrections to the k_t -factorization formula [13] and a

²A rough estimate of the values of Bjorken- x proven in a hadronic collision can be obtained using $2 \rightarrow 1$ kinematics $x_{1(2)} \sim \frac{p_t}{\sqrt{s}} e^{\pm y}$, with \sqrt{s} , p_t and y being the collision energy and the transverse momentum and rapidity of the produced hadron respectively.

³Here we just mention here a few well known examples; a rather exhaustive compilation of phenomenological works to for the description of particle production in HIC can be found in e.g [5].

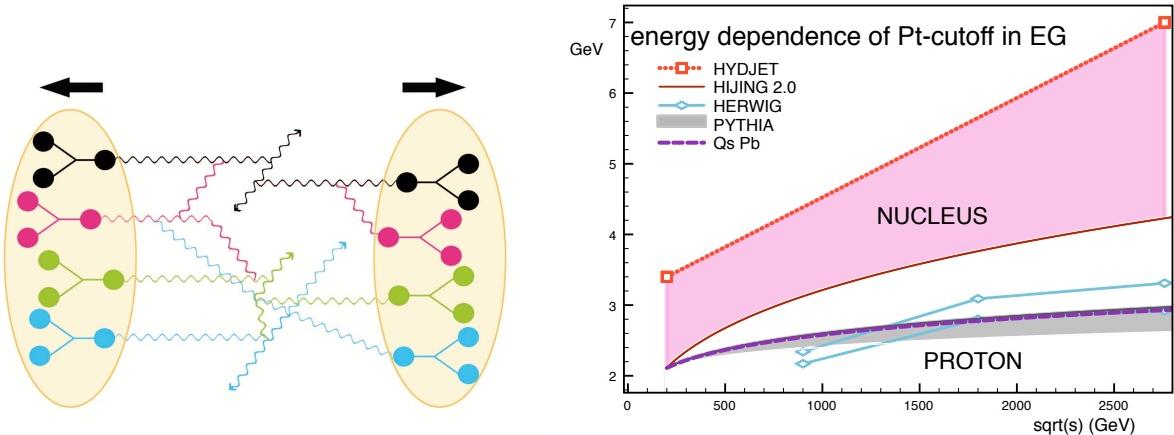


Figure 1: Left: Schematic representation of coherence effects in heavy ion collisions. Right: Energy-dependence of the transverse momentum cutoff in MC event generators for proton-proton collisions (two different PYTHIA tunes) and heavy ion collisions (HYDJET and HIJING). Also shown the characteristic value of the saturation scale $Q_s \sim \sqrt{s}^{0.15}$.

proof of factorization of multiparticle production processes at NLO [14]. Furthermore, our knowledge of exclusive particle production and multi-particle correlations (di-hadrons, hadron-photon etc) has been advanced significantly through a series of recent works that establish the precise relation between the n -point functions of the nuclear wave function and the observables of interest [15, 16]. Thus, and despite the intrinsic technical difficulty of higher order calculations in the CGC –one should recall that they are performed by expanding on a strong background color field– progress on the theoretical side has been steadily delivered over the last years.

Notwithstanding the progress brought by these works, the CGC framework is still far from the degree of sophistication and accuracy that characterizes standard pQCD methods based on the collinear factorization formalism and DGLAP evolution equations. The reasons for this are manifold: First, the new theory tools discussed above have not been yet fully implemented in a systematic way in phenomenological applications. Current descriptions of data combine NLO with LO theory ingredients in a somehow uncontrolled theoretical scheme. For instance, the –arguably– most ambitious effort so far to determine the universal properties of nuclear and proton wave functions at small- x in a systematic way is provided by the global AAMQS fits to e+p data[17, 18] and their extension to the nuclear case through Monte Carlo methods [19]. The AAMQS fits are rely on the use of the running coupling BK equation to describe the small- x evolution of the 2-point function, but then use the LO dipole formalism to calculate the γ^* -proton cross section. Related issues obscure the successful phenomenological descriptions of data in single [20] and double [21] inclusive production in p+p and d+Au collisions or the widespread use of k_t -factorization in models for total multiplicities, known not to be valid in the case of *dense-dense* scattering. Most of the NLO tools being available, the main obstacle to fix such insufficiencies of present phenomenological works is the difficulty of their technical implementation. NLO and exclusive particle production calculations typically require the knowledge of the x -dependence of n -point functions beyond the 2-point function. Hence, the use of the (running coupling) BK-equation for the 2-point function, easy to solve numerically, is no longer sufficient and solutions of the full B-JIMWLK hierarchy of coupled equations –more demanding numerically– are needed. A promising analytic method to solve B-JIMWLK equations through a Gaussian approximation that allows to obtain arbitrary n -point functions in terms of the 2-point one has been proposed recently [22], and its practical implementation would substantially reduce the uncertainties progress related to calculations on di-hadron correlations.

Other factor that blurs the predictive power of the CGC framework is the paucity of experimental data on high-energy (equivalently, small- x) nuclear reactions. Such information is needed to constrain the non-perturbative parameters of the theory, like the initial conditions for the evolution at some initial scale (x_0 typically taken to be $= 10^{-2}$ in practical applications) or the impact parameter dependence of the nuclear unintegrated nuclear distributions. Lacking such information, some degree of modeling is unavoidable. Mean field approaches for the description of the nuclear geometry have been recently superseded by Monte Carlo methods as the MC-KLN or MC-rcBK ones [23, 19], where the position of nucleons in the transverse plane are treated as a random variable, thus allowing to account for geometry

fluctuations in the collision process.

Keeping in mind the present limitations of CGC phenomenological works discussed in this section, let me now briefly review current CGC predictions for different observables at the LHC in the next sections.

3. Multiplicities

The CGC offers a very economical description of the integrated hadron multiplicities produced in heavy ion collisions. Based solely in dimensional analysis, the number of particles produced per unit of transverse area rises proportional to the saturation scale (in symmetric collisions)

$$\frac{dN}{d\eta d^2b} \Big|_{\eta=0} \sim Q_s^2(\sqrt{s}, b). \quad (1)$$

Such approximate expression can be realized either via solutions of the classical equation of motion in the presence of sources (projectile and target) or –less rigorously for A+A collisions– through the use of k_t -factorization. It accounts well for two of the most remarkable features observed in RHIC d+Au and Au+Au data as well as in LHC Pb+Pb data: *i*) Approximate factorization of the collision energy and collision centrality of total multiplicities and *ii*) Power-law dependence on integrated multiplicities on collision energy. In Fig 2 we show the predictions for the rapidity dependence of hadron multiplicities from different CGC models rooted in k_t -factorization, where particle production is given by the convolution of the unintegrated gluon distributions of projectile and target. These models differ mainly in their input for the nuclear unintegrated gluon distributions and in the treatment of the geometry dependence –either Monte Carlo methods or mean field approaches– but also in the implementation details like the IR regularization or the rapidity to pseudo-rapidity Jacobian or the modeling of the large- x component of the corresponding wave functions (hence the large deviations among them at more forward/backward rapidities). They have been tested against d+Au RHIC data and then extrapolated to LHC energies without further adjustments. Overall they predict a charged hadron multiplicity

$$\left. \frac{dN_{ch}^{p+Pb}(\sqrt{s} = 5 \text{ TeV})}{d\eta} \right|_{\eta=0} \approx 17 \pm 2. \quad (2)$$

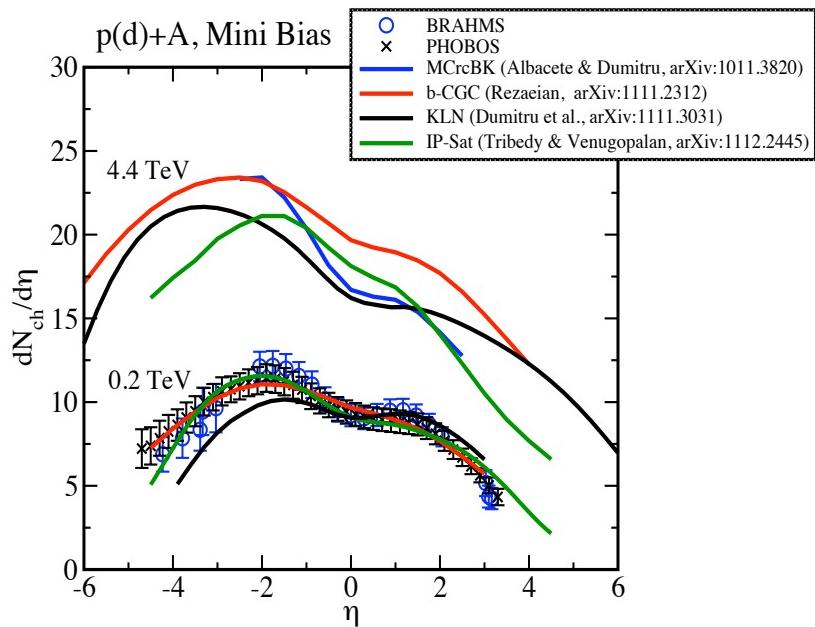


Figure 2: A compilation of CGC-based predictions for the rapidity distribution of integrated hadron multiplicities in p+Pb collisions at the LHC: MCrcBK [19], b-CGC [24], MC-KLN [25] and IP-Sat [26]. Fig courtesy of A. Rezaeian.

4. Nuclear modification factors

An observable that has centered much of the discussion on the relevance of CGC physics in heavy ion collisions is the nuclear modification factor measured in d+Au collisions at RHIC. At mid-rapidity RHIC data show a moderate enhancement of single inclusive particle production typically attributed to semi-classical multiple scatterings, whereas they are continuously depleted at more forward rapidities. A good quantitative description of this forward suppression is possible within the CGC [20], where it relates to the non-linear evolution of the nuclear ugd. However, RHIC forward data falls very close to the kinematic limit, where large- x effects such as energy loss –neglected in the in the CGC approach– may also be relevant. Indeed, there are alternative explanations of data where energy loss is the main dynamical ingredient (see e.g [27]). Moreover, the CGC description of the most forward data on neutral pions performed by the STAR collaboration requires the use of K -factors smaller than unity, hinting at the relevance of large- x effects.

Although more exclusive observables like di-hadron or hadron-photon correlations are expected to better discriminate between different approaches, a first test for models of particle production in HIC shall come from data on inclusive multiplicities and single particle distributions as they are much easier to obtain experimentally. Generic arguments based on kinematics suggest that one should expect a similar suppression of the nuclear modification factors in LHC p+Pb collisions at mid-rapidity as the one observed in forward RHIC d+Au data, since in both cases the nuclear wave function is probed at similar values of Bjorken- x . While this argument can be a somewhat misleading (the proximity of RHIC forward data to the kinematic limit limits strongly the transverse momentum of the gluons probed in the nuclear ugd), it is approximately realized in the different CGC-predictions. Fig 3 show the predictions for R_{pPb} at rapidity 0 (left) and 2 (right) based from the rcBK MC [28] and IP-Sat [26] models. They predict a moderate suppression (similar to the one observed at RHIC $\sim 0.6 \pm 0.7$ at moderate to small transverse momentum $p_t \lesssim 3 \pm 4$ GeV, and a smooth approach to unity at larger transverse momentum. The error bands in the MC-rcBK calculation originate from the use of different initial conditions to solve the running coupling BK evolution and also from the variation of factorization scales and fragmentation functions in the k_t -factorization formula they rely upon. Also, it should be noted that the MC-rcBK predictions presented here correspond to the *quenched* approximation for the nuclear geometry. The details of this calculation will be presented in [28]. Remarkably, the CGC predictions for mid-rapidity overlap strongly with those obtained within the collinear factorization framework using the EPS09 parametrization for the nPDF's (results from [29]). One then concludes that only this observable does not suffice to discriminate among different approaches to particle production in high energy heavy ion collisions. The differences between CGC and collinear factorization formalisms start becoming apparent as one moves to more forward rapidities. CGC models predict a faster onset of the suppression at higher values of transverse momentum with respect to the EPS09 results. The weak rapidity dependence of EPS09 results can be traced back to the flatness of the gluon modification factor at small- x in this parametrization. Thus, a rapidity scan of the nuclear modification factors would offer a much larger discriminating power.

CGC predictions at intermediate values of rapidity suffer of a systematic uncertainty: In the CGC there are two distinct but related approaches to hadron production in high energy asymmetric collisions. Particle production processes in the central rapidity region probe the wave functions of both projectile and target at small values of x . Here, one may employ the k_t -factorization formalism where both the projectile and target are characterized in terms of their rcBK evolved unintegrated gluon distributions (UGDs). However, at more forward rapidities, the proton is probed at larger values of x while the target nucleus is shifted deeper into the small- x regime. Here, k_t -factorization fails to grasp the dominant contribution to the scattering process. Rather, the *hybrid* formalism proposed in ref. [30]. In the hybrid formalism the large- x degrees of freedom of the proton are described in terms of usual parton distribution functions (PDFs) of collinear factorization which satisfy the momentum sum rule exactly and which exhibit a scale dependence given by the DGLAP evolution equations. On the other hand, the small- x glue of the nucleus is still described in terms of its UGD. The corresponding limits of applicability of each formalism –equivalently the precise value of x at which one should switch from one to the other– have only been estimated on an empirical basis, and in practice it is taken to be $x_0 \sim 10^{-2}$.

The Leading Order hybrid formalism yield a stronger suppression than the k_t -factorization one (see Fig 2 right). Recently the hybrid formalism has been improved through the calculation of inelastic contributions and full NLO corrections that may become important at high transverse momentum [12]. The inelastic terms were recently implemented in phenomenological work [31]. There it was observed that the effect of the inelastic corrections is to slightly

increase the value of the nuclear modification factors with respect to the LO result, thus bringing them closer to the results obtained within the k_t -factorization framework. A full phenomenological implementation of the hybrid and k_t -factorization at NLO is necessary to better assess this systematic uncertainty.

At a strictly qualitative level, two generic features of CGC predictions can be highlighted:

- a) : Disappearance of the Cronin peak in R_{pPb} at central rapidities.
- b) : Stronger suppression at forward rapidities: $R^{pPb}(y_1, p_t) > R^{pPb}(y_2, p_t)$ for $0 > y_1 < y_2$.

These two features of CGC predictions originate from generic properties of the non-linear small- x evolution, regardless of the degree of accuracy of the evolution kernel, NLO or LO etc. Therefore, the persistence of the Cronin peak in R_{pPb} at the LHC would be very difficult to accommodate in the CGC framework. Similarly the continuous depletion of nuclear modification factors reflects the relative enhancement of non-linear correction to the evolution of nuclear wave function with respect to that of a proton.

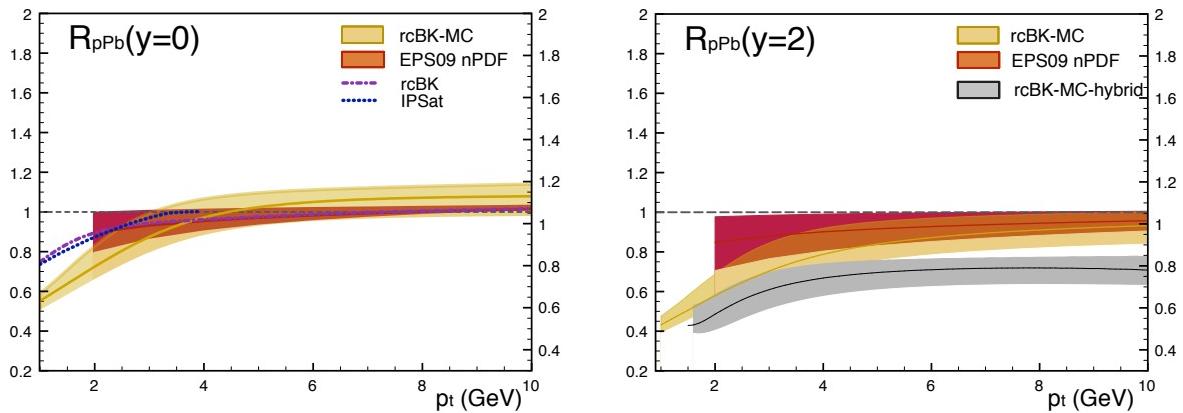


Figure 3: MC-rcBK [28] and IP-Sat [26] (dashed lines in left plot) predictions for the nuclear modification factors for neutral pions at the LHC at rapidities 0 (left) and 2 (right). The dashed lines The yellow or grey bands shown at $y = 2$ correspond to results obtained within the k_t -factorization or hybrid formalism respectively. Also shown in red the predictions corresponding to the EPS09 nPDF set within collinear factorization [29] (courtesy of P. Quiroga-Arias).

5. Two-particle correlations

The study of forward di-hadron correlations in d+Au azimuthal correlations at RHIC has provided the most solid indication for the relevance of CGC effects in data so far. The disappearance of the away side peak –also dubbed *monojet* production– in more central collisions (and its persistence in more peripheral collisions and p+p collisions) can be related to the interplay between the transverse momenta of the produced hadrons and the one acquired during the interaction with the nucleus. In the CGC approach the interaction with the nucleus is realized in a fully coherent way, and the momentum broadening is parametrically controlled by the x -dependent saturation scale of the nucleus. The latter, in turn, is described by means of the rcBK equation. A first semi-quantitative description of the data was provided in [21]. This work neglected some leading in N_c terms which calculation demands knowledge of higher n -point functions and also the contribution of the gluon channel to the production process. These caveats were partially fixed in a later work [32], where the small momentum imbalance approximation was used. Moreover, the role of multiparton interactions that may enhance the contribution of the uncorrelated component of the double inclusive cross section (specially in the forward region) [33] has not been fully explored in present CGC calculations. Nevertheless, the description of data is good in these two works is good, see Fig 4. Recently, another description of data based in a higher-twist calculation that also includes nuclear shadowing and cold nuclear matter energy loss has become available [34]. A full CGC analyses of data on di-hadron correlations including the missing ingredients in previous CGC analyses is now underway [35]. It should serve as the reference to generate precise quantitative predictions for p+Pb collisions at the LHC. So far, qualitative expectations indicate that analogous suppression of

azimuthal correlations should be observed in at the LHC. Generically the strength of the decorrelation is expected to be stronger with: *i*) increasing rapidity of the produced pair; *ii*) increasing collision centrality and *iii*) decreasing transverse momentum of the trigger and associated particle.

It has been recently proposed that hadron-photon [36] and hadron-dileptons [37] correlations may exhibit similar azimuthal structure. These observables offer the advantage that they can be computed in terms of only the rcBK-evolved 2-point function. Although their experimental determination may be more complicated, their measurement at the LHC would provide additional constraints to determine the underlying dynamics of multiparticle production in high-density QCD scattering.

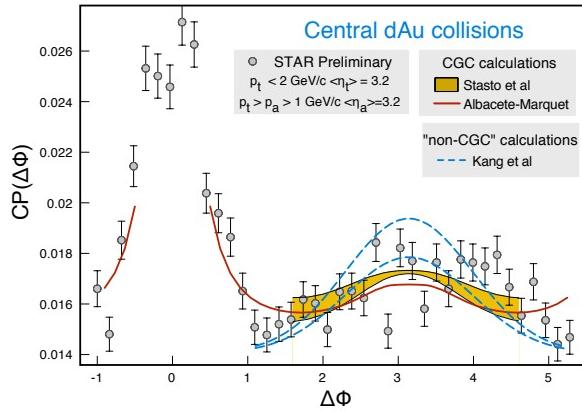


Figure 4: Comparison of STAR preliminary data [38] for the Coincident Probability between pairs of hadrons as a function of the relative azimuthal angle in d+Au collisions at RHIC. The theoretical results correspond to two CGC-based calculations[21] and [32] and a *higher-twist* one [34].

6. Conclusions

In summary, while it is fair to say that a large number of observables in different systems –from e+p to A+A collisions– that probe the small- x component of the wave function of the projectile or target find their natural interpretation in terms of high gluonic densities and also a good quantitative description in terms of CGC-based calculations, no conclusive claim for the observation saturation physics can be performed yet. Important steps have been taken over the last years in promoting the CGC framework to a predictive and quantitative phenomenological tool. Such has been possible through the systematic implementation of global fit and Monte Carlo methods and, more importantly, through an intense theoretical work in the determination of higher order corrections to the formalism, including running coupling corrections to non-linear evolution equations and also to particle production processes. Nevertheless, this program is far from complete and there is still a large margin for improvement in the CGC phenomenological works. The p+Pb data will provide precious information to sharpen the CGC quantitative tool. First of all it will provide empirical information needed to constrain the non-perturbative parameters of the theory. Next it will allow to test the generic CGC predictions and also whether the present degree of accuracy of the CGC effective theory is sufficient to quantitatively describe data.

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